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Leszek MINDUR[1], **Maciej MINDUR**[2]

THE DEVELOPMENT OF HIGH-SPEED RAIL IN THE FEDERAL REPUBLIC OF GERMANY BETWEEN 2002-2020

Summary. This article shows the development of high-speed rail in the Federal Republic of Germany (FRG), its development stages and the shipping companies dealing with this business activity. Special attention was given to the progress in the technical solutions of the track infrastructure as well as during the build of the rolling stock and engines. The high-speed rail was presented in the context of the general development of the economy and transport in Germany. This article contains a synthetic approach to the effects of the functioning of high-speed rail and its financing, as well as further directions and development prospects. Also, this article is based on thoughts, authors' own research and factual sources of polish and western literature.

Keywords: economy of FRG, high-speed rail, passenger transport

1. INTRODUCTION

High-speed rail is the most modern and advanced technology of passenger transport on land. Its main advantage is reaching high speeds of 200-300 km/h, significantly reducing the travel

[1]International University of Logistics and Transport in Wrocław, Sołtysowicka 19B Street, 51-168 Wrocław, Poland. Email: lmindur@vp.pl. ORCID: https://orcid.org/0000-0002-9177-6749
[2]Lublin University of Technology, Nadbystrzycka 38 Street, 00-618 Lublin, Poland. Email: m.mindur@pollub.pl. ORCID: https://orcid.org/0000-0002-5083-1975

time compared to covering the same distance by regular rail. Whereas it seriously competes with fast air transport.

High-speed rail requires special wagons and a special engine as well as proper infrastructure, the turning radius of which is much bigger, solid and with a firm base.

Usually, such infrastructure is built from scratch, hardly ever is it adapted to existing infrastructure to match the high-speed rail.

To make high-speed rail work, not only special trains and rails are required but also railway stations and ticket systems.

We need to emphasize that the completion of the investment in this type of transport is very capital-intensive.

Nevertheless, the required high development expenses compensate for:

- great comfort and short journey time,
- enormous impact on the economic development of the regions and the country,
- high safety level and relatively low negative impact on the natural environment compared with other transport branches,
- high efficiency of energy,
- low exterior costs.

The above reasons resulted in the dynamic development of transport in high-speed rail technology in wealthy countries of Europe and Asia.

In the FRG, the era of high-speed rail for passengers started in 1991 with the introduction of ICE 1, running on line ICE 6 between Hamburg and Munich. Since then, the extension of high-speed rail has been progressive. Some routes have been refurbished, others are brand new lines which run along or nearby existing routes, while the rest are brand new projects built from scratch.

2. COUNTRY CHARACTERISTICS

The Federal Republic of Germany is situated in the central-western part of Europe. Apart from Poland, it borders eight other countries. Germany covers 357 000 square kilometres. The country consists of 16 constituent states called ‘lands’ (Figure 1). Federalism in Germany is much more than just a state system. Its domain is internal security, education, including higher education, administration at the local government level and culture. Its main characteristic is a specific regional identity deeply rooted in tradition. Lands vary considerably from one other. For example, North Rhine – Westphalia is the most populous, with 17.9 million people.

Baden-Wurttemberg is economically the most powerful region in Europe.

Bremen has the largest land space, covering an area of 420 square kilometres with a population of 679 000 inhabitants. Bavaria covers the largest area - 705 40 square metres. While the capital city of the country – Berlin, has the largest population density – 4012 inhabitants per square kilometre. [2].

Germany is bordered by the Baltic Sea and the North Sea in the north, which with their extensive coastlines, account for numerous islands, peninsulas, bays and straits.

Arable land covers 48% of the whole area and woodland 30%.

The geological structure of Germany is very diverse – mountain areas, highlands and lowlands.

Fig. 1. Federal States of Germany [2]

We can distinguish four main physical-geographical parallel units, differing in geological structure and landscape type:

- German lowland – situated in the North of Germany. The landscape is dominated by flat plains covered in swamps and moraine uplands. The biggest rivers of the country flow along the lowland: Rhine, Ems, Elbe, Weser and bordering rivers such as Oder and Neisse;
- German highland – upland area dominating the landscape of central and southern Germany;
- Swabian-Bavarian highlands – foreground of the northern part of the Alps situated in south-western Germany called the alpine foothills;
- The Alps – a chain mountain range of Northern Limestone Alps, divided into the Allgau Alps in the North and the Berchtesgaden Alps in the South [2].

The population of Germany at the end of 2020 was 83.2 million people. There are 230 people per square kilometre, making Germany the densest populated country in Europe. However, there are differences between the northern part and the area previously known as the GDR.

In the new lands and eastern Berlin, there are 140 people per square kilometre. The density of the population in the northern part is visibly higher, 267 people per square kilometre.

The official language in Germany is German. There are numerous dialects all over the country, such as Bavarian, Saxon, and Berlin dialects. Over 7 million foreigners live and work in Germany. There are many Turkish, Serbian, Italian, Greek, Bosnian and Herzegovinian, Polish and Croatian residents there [24].

3. EVALUATION OF THE ECONOMIC SITUATION BASED ON BASIC VARIABLES IN THE YEARS 2002-2020

For many years, the Federal Republic of Germany has been the 4th biggest economic power according to its GDP (competing with the USA, China and Japan).

It also leads at creating the GDP in the European Union. Its contribution to the European community is significant, for example, in 2015, the German GDP formed 27% of the European community GDP.

In 2020, the result was slightly lower, 25.1%, but we need to look at it from a wider perspective and context to notice that economic development, as well as economic decline, affected not only other EU countries but also other countries of the world, due to COVID-19.

Table 1 shows the percentage changes in basic macro-economic rates in Germany.

Tab. 1

Basic macro-economic rates of the German economy in the years 2002-2020 (annual changes in %) [11]

Specification	2002	2003	2004	2005	2006	2007	2008	2009	2010
GDP	0.0	-0.2	0.8	1.1	2.6	1.8	1.0	-4.7	4.2
Private consumption	-0.8	-0.1	-0.3	0.3	0.8	0.3	-0.1	-0.1	0.6
Investment	-6.1	-1,6	-0.4	0.9	7.5	3.6	1.6	-9.5	5.3
Employment	69.9	69.2	71.0	71.1	71.1	72.3	72.3	73.2	74.0
Unemployment	7.6	7.2	9.2	9.1	8.0	8.3	8.2	7.8	7.3
Inflation	1.4	1.0	1.8	1,9	1.7	2.2	1.7	0.8	1.1
Public debt	60.2	63.8	66.0	68.0	68.2	64.9	66.3	73.1	82.0
Export	4.3	2.3	8.8	7.1	10.4	6.2	2.8	-14.3	14.4
Import	-1.4	5.3	6.2	6.7	10	5.3	5.8	-9.7	12.9
Public finances balance	-3.9	-3.7	-3.3	-3.3	-1.7	0.3	-0.1	-3.3	-4.4
Specification	2011	2012	2013	2014	2015	2016	2017	2018	2019
GDP	3.9	0.4	0.4	2.2	0.2	2.2	2.7	1.1	1.1
Private consumption	2.3	0.7	0.8	1.2	2.4	2.4	1.4	1.4	1.6
Investment	7.4	-0.2	-1.3	3.2	1.7	3.8	2.6	3.4	1.8
Employment	75.4	75.8	76.3	76.7	76.9	77.6	78.2	78.9	79.6
Unemployment	6.6	5.5	5.1	5.0	4.7	4.4	3.9	3.6	3.2
Inflation	2.5	2.1	1.5	0.8	0.2	0.0	1.1	0.7	0.7
Public debt	79.4	80.7	78.3	75.3	72.0	69.0	64.7	61.3	58.9
Export	8.3	2.9	1.0	4.8	5.4	2.5	4.9	2.3	1.1
Import	7.3	0.1	2.7	3.9	5.8	4.5	5.2	3.9	2.9
Public finances balance	-0.9	0.0	0.0	0.6	1.0	1.2	1.3	1.9	1.5

According to data from Eurostat in Table 1 above, the GDP of the German economy declined twice: in 2009 and 2020. The first drop was caused by the worldwide economic crisis related to the real estate market in the USA and the second one was due to the COVID-19 pandemic. We also need to emphasize that the GDP recorded a significant leap in 2010 and 2011.

Analysis of employment and unemployment is quite interesting because the German economy in the first part of the period considered was characterized by a sharp, high unemployment rate that reached 9.2% in 2004. This problem was so severe that vast labour market reforms had to be implemented. The plan was developed in 02, however, it was introduced in the following years, thus resulting in real benefits. In 2008, unemployment started to decrease and eventually dropped down to 3% in the final part of the period considered. In 2011, Germany opened up its labour market, significantly influencing employment increase in its economy.

A fundamental indicator, the public debt, was widely discussed through public opinions and in political centres.

Until 2012, this indicator experienced constant growth, which was alarming for economic independence and economic condition. German authorities applied the "debt brake", which became a highly effective solution, and by the time of the pandemic, the debt was gradually decreasing. Since 2020, it has become a convenient tool for fighting economic crises.

The inflation level process is noteworthy in the given time series. It was not a threat to the economy, even during the crisis. The condition of the German economy, according to the theory of economy, is constantly pro-development, stimulating and healthy.

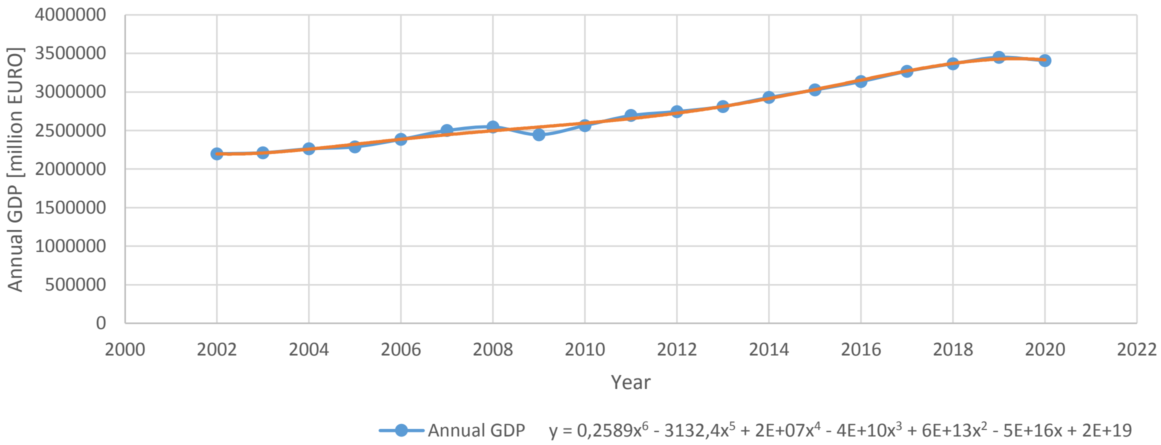

Fig. 2. Development of the GDP of the German economy in 2002-2020

Figure 2 Represents the GDP growth rate for the German economy in the period considered, developed based on the data [11]. It can be noticed that the trend line based on a polynomial of degree 6 tends to increase until 2020. Examining the credibility of indicator R^2 revealed that this analysis was well conducted; the result obtained of 0.992 is very high and close to 1.

4. TRANSPORT IN GERMANY

The Federal Republic of Germany has a well-developed transport infrastructure. Most of the transport network is formed by roads for road transport. In 2020, the total road network was 229 720 kilometres; highways constitute the highest share in this structure – 13 190 kilometres and national roads – 37 830 kilometres. The highway network was systematically expanded (in 2014 - 1290 kilometres).

Tab. 2

Transport infrastructure in FRG in 2020 (in thousand kilometres) [11]

Type of transport infrastructure	Length
Roads, including:	229 720
Highways	13 190

National roads	37 830
Local roads	86 900
County roads	91 840
Railway lines	38 470
Inland waterways	7300
Pipelines	2400

Pipeline infrastructure remains at the same level. Inland waterways, on the other hand, decreased by 4000 kilometres compared with 2014. The Federal Republic of Germany owns a huge amount of railway infrastructure, which reflects in the transport work and the amount of transport work in general.

In 2007, road transport reached the level of 343.4 billion tkm (tonne-kilometre), the biggest amount in the period considered.

According to the data presented in Table 3, transport work, especially transport branches, decreased in 2009. This situation was caused by the significant decrease in imports and exports within the German economy.

Tab. 3

Transport work in 2002-2929 (in billion km) divided into transport branches [11]

Transport branch	2002	2003	2004	2005	2006	2007	2008	2009	2010
Road	285.2	290.7	303.8	310.1	330	343.4	341.6	307.6	313
Railway	76.3	78.5	86.4	95.4	107	114.6	115.7	95.8	107.3
Inland waterway	64.2	58.1	63.7	64.1	64	64.7	64.1	55.5	62.3
Pipeline	15.2	15.4	16.2	16.7	15.8	15.8	15.7	16.0	16.3
Transport branch	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**
Road	323.8	310.1	305.8	310.1	306.0	315.8	313.1	316.8	311.9	304.6
Railway	113	95.4	111.9	112.6	116.6	126.7	117.4	117.9	119.5	109.0
Inland waterway	55.6	64.1	59.7	59.1	55.3	54.3	55.5	46.9	50.1	46.4
Pipeline	15.5	16.7	18.2	17.5	17.2	18.8	18.2	17.2	17.6	16.7

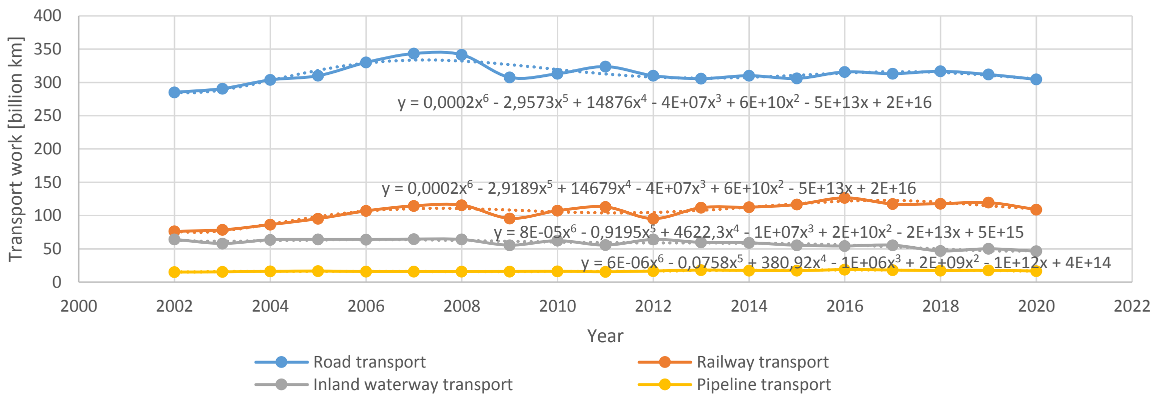

Fig. 3. Development of transport work in 2002-2020, especially transport branches in Germany

Data presented in Table 3 and Figure 2 depict precise German transport trends. Railway transport benefits from the visible growth. In 2002, railway transport reached 76.30 billion tkm, while at the final stage of the period considered, the year 2020 – 109 billion tkm. In 2016, railway transport reached its peak at the highest level so far –126.70 billion tkm.

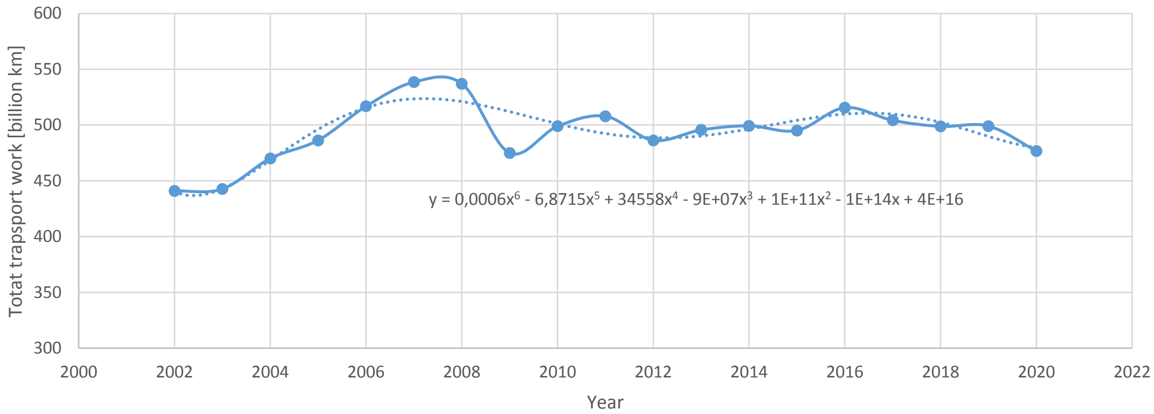

Fig. 4. Total transport work in 2002-2020 (in billion tkm)

Figure 4, based on data [11], presents the transport work in general in the German economy. Trend line shows two increase trends – 2003-2007 and 2012-2016. The trend line was based on a polynomial of degree 6. The credibility indicator R^2, in this case, is lower; nevertheless, the conducted analysis can be considered correct.

Figure 5 presents the increasing trend line of the GDP in Germany together with the transport work done. Calculations have been made upon a polynomial of degree 6. Both curves shown in the chart have a high value of R^2. Characteristics of the curve depicting the GDP show an increase at a greater inclination than the curve illustrating the transport work, which should be interpreted as slower growth of transport work compared to the GDP growth. Simultaneously, it means that in the German economy, the involvement of transport work in GDP steadily decreases.

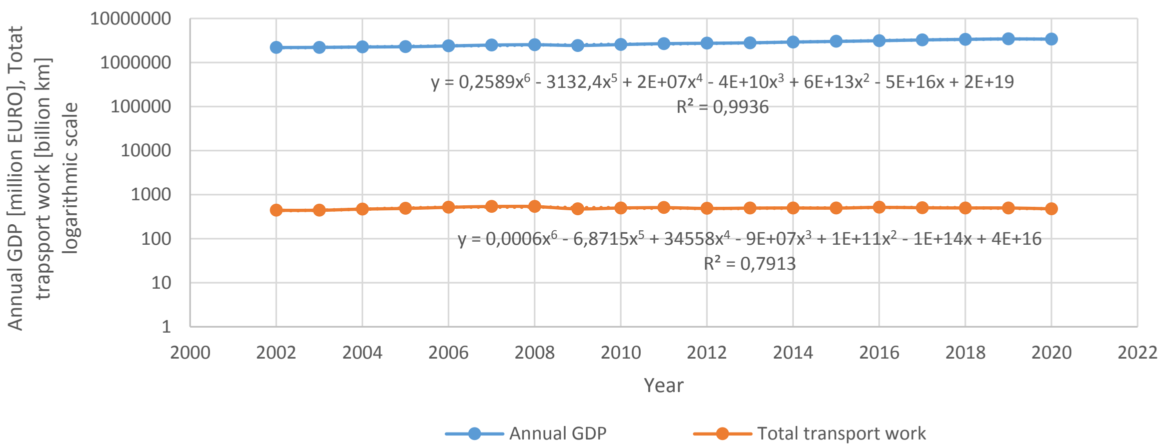

Fig. 5. GDP of Germany and transport work in general in 2002-2020

This means the right direction of economic development because expenses on the transport business for achieved effects in particular parts of the economy are getting progressively lower. With the transport intensity decrease, we may also expect reducing the basic value of goods and lowering costs of production. In conclusion, the drop in transport intensity should result in a price drop in products and raw materials.

5. CHARACTERISTICS OF A HIGH-SPEED RAIL

With dynamically developing trade in the era of high transport needs, various transport branches require coordination, support and promotion of further development of eco-friendly branches. This would reduce transport costs as well as cause a positive effect on the natural environment and reduce the negative impact on it.

Railway transport, is in many ways, an eco-friendly branch. Its features are enumerated below:

- low emission of air pollution;
- relatively low power use;
- low land-consumption;
- lower external costs [33].

High-speed rail is the most dynamically developing sector of rail passenger transport. The range of ‘High-speed transport’ is extremely wide. From the technical point of view, such transport begins at the point where the “classical” rail ends [31].

High-speed rail exceeds regular rail in terms of speed. Further, high-speed rail for passenger transport starts from 200 km/h, as considered in the literature on the subject.

Apart from trains adapted to high speed, this kind of rail also requires specific infrastructure, railway stations and separate ticket systems.

The main benefit of high-speed rail is providing fast passenger transport between destinations.

Covering long distances by rail is more comfortable and convenient than travelling by any other means of transport.

Moreover, high-speed rail ensures freedom during a journey and provides access to a restaurant, electricity network and fast internet.

6. ACTIONS LEADING TO INCREASING TRAIN SPEED IN 200-2020

Deutsche Bahn is the biggest rail company in Germany, which deserves to be called a reliable rail carrier. Deutsche Bahn trains have outstanding levels of comfort and efficiency. Thanks to high-speed trains, Intercity and regional trains, the Deutsche Bahn ICE map is one of the biggest in Europe, as can be seen in the picture of the railway network in Germany (Figure 6).

The red line shows the lines adjusted to the speed limit of 300 km/h, the yellow line – 250 km/h, dark blue – 200 km/h and blue – the remaining lines adapted to the maximum speed of 160 km/h [9].

Fig. 6. German railway network [20]

Deutsche Bahn owns high-speed trains called ICE (InterCity Express). DB ICE Trains are used on popular long-distance routes all over the country. They operate between big cities such as Munich, Berlin and Frankfurt. Also, they can reach speeds of more than 300 km/h. With the ICE train, one can also reach other countries, such as France and Austria. Train equipment is very robust, and most of them offer Wi-Fi access. ICE trains offer two classes of seats, and both are very comfortable. In the first class, passengers are offered free newspapers, free hot and cold drinks and snacks [9].

The order for 16 advanced high-speed trains for Siemens in 2008-2011, to be implemented in Germany, Belgium and France, worth 500 million euros, indicates the dynamic development of DB company.

ICE 3, or InterCity Express 3, is a train family operating in Germany. It differs from other trains due to its lack of a regular wagon (power car), which provides the vehicle with additional speed. It was replaced by placing traction motors along the train so that passengers can use the whole deck – including the first wagon, where the engine driver is only separated from passengers by a plastic glass. The top speed reached by this vehicle was 368 km/h [14].

In May 2011, the German national rail concluded a framework agreement with Siemens Mobility for 300 trains. It was then the biggest rail contract that Siemens had ever signed in its 170-year-old history.

Velaro D is an extension of ICE 3 trains that were previously introduced to cross-border use between Germany, France and Belgium. It consists of eight single wagons and can seat 460 passengers, which is 30 passengers more than its previous version.

The traction power is 8000 KMW and allows it to reach a speed of 320 km/h.

ICE 3, like its previous models, has traction motors placed under the floor and allocated along the train to enable lightning-fast acceleration.

An environmentally friendly electric braking system transfers braking energy straight back to the power system [19].

In December 2013, the Federal Railway Office (EBA) approved the operation of Velaro D trains on the DB railway network. The authorization also included trains operating on multi-unit mode and double-traction mode. Two test trains were delivered in November, followed by another two, and finally, four additional were planned to be delivered in the spring of 2014.

Based on the previous arrangements with DB, the outstanding 8 out of 16 trains ordered initially were reserved for a test run in Belgium and France [14].

Moreover, in December 2013, a brand new ICE 3 407, based on the Velaro platform by Siemens, was approved to be used in Germany. These trains were directed to Cologne – Frankfurt am Main – Stuttgart. The 407 series is characterized by lower power use and higher technical reliability, as well as better aerodynamics [8].

In 2015, a new high-speed line between Erfurt – Leipzig/Halle was completed. The 123 km long route was adjusted for various train types, cargo and passenger, including ICE 3. The implementation of the project allowed the reduction of the journey by half.

The new line was considered the most modern line in Germany. European train steering system (ETCS) was introduced to guarantee interoperating of railway transport, eliminating signalling devices, including semaphores.

Due to the solid construction of tracks made from steel and concrete, high-speed trains can reach speeds of 300 km/h. This modern construction cost 2.8 billion euros, and its execution took over half a century, dating back to the year 1990 [28].

In 2016, a new era began, together with ICE services for Deutsche Bahn, when the biggest order in the history of Siemens Mobility for ICE 4 was made.

It was decided that the long-distance DB fleet should benefit from the new 100 12-wagon trains and 19 7-wagon trains of the new series.

The maximum speed of ICE 4 is 250 km/h, which is less than the ICE 3 series running 300 km/h. But ICE 4 are supposed to replace the older generation trains, providing enormous savings for DB due to the passenger seats increase and a 30% energy use decrease than ICE 1 and ICE 2 [18].

By 2024, Siemens Mobility will have provided 137 ICE 4 trains [30].

In 2016, Deutsche Bahn and Siemens launched a pilot application for predictive servicing and conservation of high-speed trains Velaro D (407 ICE 3 series). The vehicle data are received and analyzed in the central diagnosis system to calculate possible failures.

These prognoses will be used by the specialists to validate orders concerning actions and transfer them straight to technicians in DB workshops in case of emergencies or planned maintenance works.

Analysis of data is based on algorithms and models that enable highly reliable and foreseeable behaviour of vehicles and components. In this way, the current vehicle condition can be monitored and appropriate actions taken [7].

In 2017, steps were taken to extend fast connections between Erfurt – Leipzig/Halle from the North with the line Berlin-Halle, and the South with line Nuremberg-Erfurt (transport corridor Berlin-Nuremberg, 500 km long). Implementation of this investment reduced the Munich-Berlin journey to 3 hours 45 min (Figure 7).

Fig. 7. Line Berlin-Nuremberg [4]

In 2017, Deutsche Bahn introduced five flag-trains ICE 4 on long-distance routes. These vehicles can be adjusted to an expected number of passengers, maximum speed or preferred route profile. ICE 4 trains are equipped with motor parts containing all useful traction components in one segment under the wagon floor. Formation of the trains takes place by combining motor parts, caboose parts, internal parts and two rear parts.

The trains are equipped with the European Train Steering System (ETCS) and run between Hamburgiem-Munich and Hamburg-Stuttgart [15]. In September 2018, Deutsche Bahn ratified a decision to order 18 7-unit ICE 4 trains, spending 700 million euros [22].

In July 2020, the company signed an agreement on the delivery of 30 high-speed compositions- ICE 3 based on the Velaro Siemens Mobility platform. In February 2022, the company decided to expand the contract and ordered an additional 43 sets of ICE trains. Increasing the DB fleet will enable it to meet the requirements of synchronizing the cross-country transport timetable, which is planned for 2030.

In December 2022, a part of the new ICE line to Stuttgart, Wendlingen-Ulm (60 km), is planned to be completed where trains can reach speeds of 250 km/h.

The construction of line Frankfurt am Main-Mannheim and towards Fuld and Wurzburg, as well as line Y' Hanover-Hamburg and Brem, have been planned for the following years[21].

At the InnoTrans Expo in 2018, Siemens company presented the new high-speed trains conception – Velaro Novo, which offers even better efficiency standards and balanced development (Figure 8). Reaching speeds of 300 km/h, the new high-speed train consumes 30% less power than previous Velaro versions, which means reducing CO_2 emission by 1375 tonnes per year. Due to the light construction, the mass of the train has also been reduced by 15%, and at the same time, the space for passengers' use has been increased by 10%. Siemens declares that the first Velaro Novo trains may be introduced in 2023 [27].

Fig. 8. Velaro Novo train [27]

7. TECHNICAL SOLUTIONS FOR TRAINS AND ENGINES – WAYS OF POWERING

ICE1 (Figure 9) and ICE 2 on the new lines reach speeds of 280 km/h (174 mph). Their interiors are the most effective of all ICE trains. ICE 1 runs on the route to Switzerland and is replaced by ICE 4. ICE 2 runs on the line Cologne – Ruhr – Hannover – Berlin [26].

Fig. 9. ICE 1 train at the railway station in Berlin [26]

Tab. 4

ICE 1 train technical data [13]

Train labelling/series	One-system train ICE 1 (class 401)
Country of transfer	Germany, Switzerland, Austria
Manufacturer	AEG, ABB, Krauss-Maffei, Krupp, Siemens, Thyssen-Henschel

Unit production costs	25 million euros
Number of trains	59
Number of power wagons	2
Original number of internal wagons	14
Internal wagons number	12
Number of seats I/II class/restaurant	Original: 144/501/40 (in total 685)
Years of construction	1989–1993
Track width	1435 mm
Powering systems	15 kV/16.7 Hz
Train steering systems	AFB, Indusi, LZB (Germany)
Maximum speed during test drive	328 km/h
Construction speed	280 km/h
Maximum speed in planned service	250 km/h
Train acceleration power	9600 kW (2 x 4800 kW)
Starting traction	400 kN

Tab. 5

ICE 2 train technical data[13]

Train labelling/series	One-system train ICE 2 (class 401)
Country of transfer	Germany
Manufacturer	Siemens, AEG, DWA
Unit production costs	18.2 million euros
Number of trains	44
Train type	Many units
Number of power wagons	1 electric
Rear wagons number	1
Internal wagons number	6
Seats number I/II class/restaurant	105/263/23 (in total 391)
Years of construction	1995–1997
Track width	1435 mm
Powering systems	15 kV/16.7 Hz
Train steering systems	Indusi, LZB, SiFa (Germany)
Technically approved maximum speed	280 km/h
Maximum speed planned by service	250 km/h
Train acceleration power	4800 kW
Starting traction	200 kN

ICE 3 trains (Figure 10) can reach up to 300 km/h (on high-speed lines in France, they can reach 320 km/h). They come in 3 versions:

– ICE 3M class 406 – adapted to international routes, Brussels/Amsterdam to Cologne/Frankfurt,
– ICE 3 class 403 –runs on the route Cologne – Munich and other routes,
– ICE 3 class 407 (close relative to Eurostar e320) – runs on the route Frankfurt–Paris [26].

Fig. 10. ICE 3M train at the railway station in Frankfurt am Main [26]

Tab. 6

ICE 3 train technical data [13]

Train labelling/series	ICE 3/class 403
Country of transfer	Germany
Manufacturer	Siemens, Adtranz
Unit production costs	18 million euros
Number of trains	50
Detailed train number	Order 08/1994: 37 trains (403 001-037) Order 02/2001: 13 trains (403 051-063)
Train type	Railway train
Power wagons number	2
Internal wagons number	6
Seats number I/II class/restaurant	Original: 144/250/24 (in total 415) Currently: 98/343/– (in total 441)
Years of construction	1995–2004
Installation	6.01.2000
Track width	1435 mm
Powering systems	15 kV/16 2/3 Hz
Train steering systems	LZB 80, Indusi PZB 90
Maximum technically approved speed	330 km/h
Maximum speed planned by service	320 km/h
Current maximum speed in plan’s service	300 km/h
Train acceleration	0.86 m/s²
Starting traction	300 kN

ICE 4 trains (Figure 11) were introduced on many German national routes, such as Hamburg – Munich. In December 2019, they took over most of the rides from ICE 1 on routes Hamburg – Switzerland and Berlin – Switzerland. Depending on the version, ICE 4 can reach speeds of 230 or 250 km/h [26].

Fig. 11. ICE 4 train at the railway station in Munich [26]

One of the key differences compared with the previous ICE version is allocating spaces for bicycles in the last wagon. It is also the first ICE to benefit from an innovative lighting system, depending on the time of the day and the most modern WiFi and telephony technology [26].

Tab. 7

ICE 4 train technical data [13]

Train labelling/series	ICE 4 (12-unit)
Country of transfer	Germany, Switzerland (Austria)
Manufacturer	Siemens, Bombardier
Number of trains	50
Train type	Railway train
Rear wagons number	2
Internal wagons number	10
Seats number I/II class/restaurant	205/625/– (in total 830)
Years of construction	2011–2025
Installation	24.10.2016
Track width	1435 mm
Powering systems	15 kV/16.67 Hz
Train steering systems	ETCS level 2, LZB, PZB
Technically approved maximum speed	265 km/h
Motors	24
Train driving power	9900 kW (24 x 412,5)
Detailed data concerning efficiency	6 wagons with a power of 1.65 MW each

ICE-T (Figure 12) is equipped with a swing body, which allows the vehicle to take faster curves on conventional routes. It is available in two versions: a 7-unit and a 5-unit train. It is possible to combine the units together and create a double-train composition. Also, the 7-unit version includes a dining car, while the 5-unit one has an onboard bistro. ICE-T runs on routes Vienna– Nuremberg–Frankfurt or Vienna–Berlin (7-wagon version) [26].

Fig. 12. ICE-T train at the railway station platform in Frankfurt [26]

Tab. 8

ICE-T train technical data [13]

Train labelling/series	ICE-T (series 411), wagon ÖBB Rh 4011
Unit production cost	11.76 million euros
Number of trains	43
Train type	Railway train
Rear wagons number	2
Internal wagons number	5
Seats number I/II class/restaurant	53/305/24 (in total 382)
Years of construction	1997–1999
Track width	1435 mm
Powering system	15 kV/16.7 Hz
Train steering systems	LZB 80/16, PZB 90, ZUB 262 (contains ZUB 121), Integra Signum device, Eurobalisa (ETCS)
Technically approved maximum speed	230 km/h train reached speeds of 253 km/h on registered rides
Maximum speed in planned service	230 km/h
Train driving power	4000 kW (8 x 500 kW)
Train acceleration power	0.5 m/s²
Starting traction	200 kN

8. LINE INFRASTRUCTURE FOR HIGH-SPEED TRAINS

Infrastructure for high-speed trains requires an appropriate adjustment. This includes:

- appropriate geometry of the route in the layout and longitudinal profile,
- high reliability of route safety,
- appropriate track construction,
- appropriate junction construction,
- special requirements concerning the platforms,
- traffic operation via cabin signalling,
- efficient powering of traction network.

High-speed lines are characterized by high-quality performance and maintenance of railway surfaces, ensuring immobility of track location, and reducing horizontal and vertical unevenness of the surface. Such requirements can be best provided by the slab track surface [31].

Standard gravel construction of railway surfaces that has been used unchanged for over 150 years is unable to secure the required durability and stability. This is caused by huge dynamic interaction together with extremely intense railway transport and high speed. The dynamic load of the track increases several times when exploited by contemporary high-speed trains. In the early 60s of the 20th century, examinations held in Germany proved that gravel is the weakest element of the railway surface. It works together with the track grate in a flexible-plastic state and causes permanent deformation of the railway surface. Vibrations caused by passing trains result in the permanent deformation of gravel. This directly influences the variability of the flexibility characteristics and damping along the track. As a result, the track geometry deforms in the plan and profile and weakens the stability of the gravel. This impacts passengers' comfort and consequently leads to speed reduction for safety. High speed of railway vehicles (220–250 km/h) cause the elevation of crushed stone due to airflow, which weakens the gravel prism. This causes burdensome and costly repairs to the railway surface. In Germany, it is believed that increasing the train speed from 160–200 km/h to 250–300 km/h increases the cost of railway surface maintenance of classic construction and needs to be doubled. The unprofitability of railway surface maintenance of high-speed lines resulted in using modern surface systems without gravel [12].

Fig. 13. The first ICE on the Filstal bridge – the highest rail bridge in Baden-Wurttemberg [17] as part of the new railway line between Wendlingen and Ulm [29]

Fig. 14. Kinding station on high-speed line Nuremberg-Ingolstadt [3]

Tab. 9

Line infrastructure for high-speed trains according to technical regulations applying to track version 20 August 2014

Cant	160 mm (max 180 mm)
Horizontal curve radius	5000 mm
Vertical curve radius	20 000 mm
Oblong inclinations	12–40‰*
Width between tracks	4750 mm
Junctions up the speed 360/160 km/h	R = 10 000/4000

***** One of the typical tunnels in Germany LDP Cologne – Frankfurt (Main) (v_{max} = 300 km/h, cant = 40‰).

High-speed ICE trains connect many big cities in Germany. Passengers can also travel to Austria (Vienna, Innsbruck), Belgium (Brussels, Liège), Denmark (Copenhagen, Arhus), France (Paris), Netherlands (Arnhem, Utrecht, Amsterdam) and Switzerland (Zürich, Interlaken).

Volume of ICE traffic within 24 hours is as follows:

- on route Cologne – Frankfurt, the amount of pairs of trains is 54;
- on route Hamburg – Frankfurt, the amount of pairs of trains is 47;
- on route Hamburg –Nuremberg, the amount of pairs of trains is 37;
- on route Berlin – Hanover, the amount of pairs of trains is 33.

Fig. 15. German high-speed railway network in Germany, 2021 [5]

Fig. 16. Amount of pairs of ICE trains within 24 hours [3]

9. METHODS OF EXTERNAL FINANCING

From 2000–2017, the EU donated 23.7 billion euros to co-finance high-speed railway infrastructure and 4.4 billion euros for ERTMS system installation on high-speed railway lines. Additionally, since 2000, the European Bank of Investment (EBI) has provided a loan of 29.7 billion euros for high-speed railway line construction. Nearly half of EU funds for KDP (over 11 billion euros) were spent on investment in Spain. A total of 21.8 billion euros – 92.7% of the whole financial resources – were granted to seven Member States (Figure 17) [1].

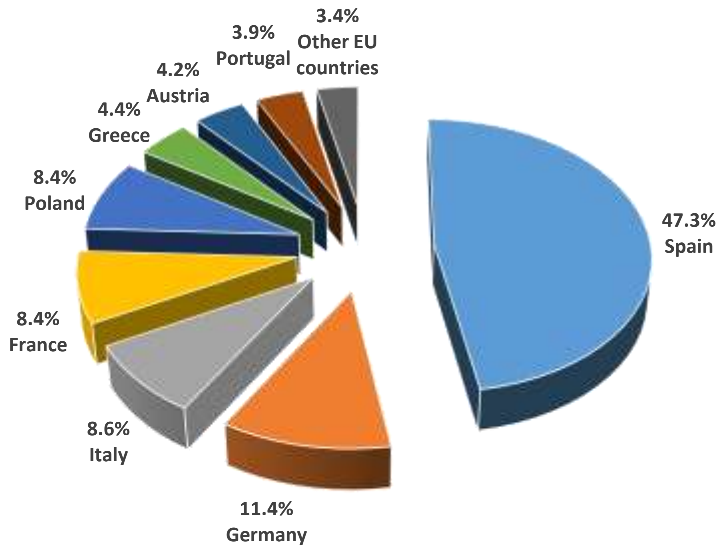

Fig. 17. High-speed trains co-financing in the EU divided into Member States (2000-2017) [1]

Financing high-speed railway in the Federal Republic of Germany:

- The sum of 86 billion euros – intended for railway infrastructure during the current decade, wherein 24 billion euros is to be invested by DB and 62 billion euros by the federal government [32]. Regardless, 12.2 billion euros will be invested in the fleet within the next 6 years. According to these plans, the average investment per year will exceed 10 billion euros;
- EU sources, covered on average, 11% of the total cost of KDP construction;
- German railway continued their investment programme called 'Neues Netz für Deutschland'. In 2022, a record amount of money (13.6 billion euros – 900 million euros more than in 2021) was intended for infrastructure development coming from own sources, federal sources and federal states [25].

10. PLANS AND DIRECTIONS FOR FURTHER DEVELOPMENT

The main directions of KDP development in Germany can be presented in the points below:

1) Maximum speeds and journey time:

Research on increasing the maximum speed up to 400 km/h in new trains is being conducted.

2) Making use of high-speed lines for regional journeys:

Regional connection systems are created on lines with sufficient capacity. Occasionally, small regional stations need to be built to enable residents of a particular region to have access to public transport. These stations might function as hubs or integrate low-traffic connections with the main connection line.

3) Creating a high-speed international network:

Creating a high-speed railway international network is one of the main priorities of the EU transport policy. Such a network was laid down in Regulation 1315/2013 and should be completed in its basic shape by 2030 and fully completed by 2050. It is supposed to cover most EU countries, which will be beneficial for the unity of big or strategically important European cities [23].

There is a plan to refurbish an 1800 km track in 2022 in Germany, as well as 2000 crossovers, renovation of 140 bridges and 800 railway stations (mainly commuting and junction stations). One of the most important events this year, 2022, will be the completion of the 60 km part of KDP Wendlingen-Ulm on line Stuttgart –Munich (Figure 14). The journey time will reduce by 15 min.

Other development elements will be:

- increasing transport punctuality (from 76.5% in 2014 to 85% in the following years – long-distance transport);
- expansion of fleet/withdrawal of older train compositions (ICE 1 and ICE 2) from 2017–2025;
- completion of the purchase of 130 ICE 4 trains from Siemens and expanding the fleet to 360 by 2029 and 450 after 2030;
- due to exchanging train compositions for newer versions, by 2020, power use would have reduced by 20% [16].

DB company foresees that by 2030, because of well-developed regional and international railway networks, the next 5 million car users will choose the railway carrier's offer instead. Increasing the number of modern and comfortable railway fleets will encourage passengers to choose this means of transport over road and air transport. The above factors will significantly increase the number of long-distance passengers (from 162 million in 2020 to 180 million in 2024 and 260 million in 2030) as well as regional connections (from 1972 million in 2019 to 2500 million in the following years) [6].

11. SUMMARY – BENEFITS AND EFFECTS OF TRAVELLING BY HIGH-SPEED RAIL

The high-speed rail is a comfortable, safe and ecologically balanced means of transport. It provides social-economic benefits to the countries and regions they support. An effective transport system is an essential factor for economic development. One main benefit of using the high-speed rail is the reduction in travel time between cities – the savings can reach 30-200%, which can result in transport speed.

Furthermore, the high-speed railway provides a high level of security and a relatively low negative impact on the natural environment. Efficient and effective transport by high-speed railway enables a high level of mobility and offers affordable, high-quality service. Subsequently, the high-speed railway has a positive influence on European integration and interpersonal contacts [10].

Benefits essential to the natural environment are:

- relatively low level of land usage (3.2 ha/1 km line per 9.3 ha/1 km highway on average);
- high power efficiency (about 3.4 times higher than a car and 8.5 times higher than in air transport);
- low level of CO_2 emission;
- high level of safety;
- low external costs (about 9 times lower than costs generated by cars and 5 times lower by airport transport) [10].

Low harmfulness of railway transport to the natural environment is primarily emphasized in public relations campaigns. The carriers typically focus on 'clean transport' and highlight it, which is of prime significance in these times of global climate change.

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